Draft version June 23, 2009
Preprint typeset using LaTeX style emulateapj v. 03/07/07

EVOLVING TO TYPE IA SUPERNOVAE WITH SHORT DELAY TIMES

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Draft version June 23, 2009

ABSTRACT

The single-degenerate model is currently a favourable progenitor model for Type Ia supernovae (SNe Ia). Recent investigations on the WD + He star channel of the single-degenerate model imply that this channel is noteworthy for producing SNe Ia. In this paper we studied SN Ia birthrates and delay times of this channel via a detailed binary population synthesis approach. We found that the Galactic SN Ia birthrate from the WD + He star channel is $\sim 0.3 \times 10^{-3}$ yr^{-1} according to our standard model, and that this channel can explain SNe Ia with short delay times ($\sim 4.5 \times 10^7 - 1.4 \times 10^8$ yr). Meanwhile, these WD + He star systems may be related to the young supersoft X-ray sources prior to SN Ia explosions.

Subject headings: binaries: close — stars: evolution — supernovae: general — white dwarfs

1. INTRODUCTION

Type Ia supernovae (SNe Ia) play an important role in astrophysics, especially in the study of cosmic evolution. They have been applied successfully in determining cosmological parameters (e.g., Ω and Λ; Riess et al. 1998; Perlmutter et al. 1999). It is widely accepted that SNe Ia are thermonuclear explosions of carbon-oxygen (CO) white dwarfs (WDs) accreting matter from their companions (for a review see Nomoto et al. 1997). However, there is still no agreement on the nature of their progenitors (Hillebrandt & Niemeyer 2000; Röpke & Hillebrandt 2005; Wang et al. 2008; Podsiadlowski et al. 2008), and this may raise doubts about the distance calibration which is purely empirical and based on the SN Ia sample of the low red-shift Universe.

At present, various progenitor models of SNe Ia can be examined by comparing the distribution of the delay time (between the star formation and SN Ia explosion) expected from a progenitor channel with that of observations (e.g., Chen & Li 2007; Xu & Li 2009; Lü et al. 2009; Mannucci 2009; Schawinski 2009). Recently, there are three important observational results for SNe Ia, i.e., the strong enhancement of the SN Ia birthrate in radio-loud early-type galaxies, the strong dependence of the SN Ia birthrate on the colors of the host galaxies, and the evolution of the SN Ia birthrate with redshift (Della Valle et al. 2005; Mannucci et al. 2005, 2006, 2008). The relation between SN Ia birthrate and radio power implicates the information on the time-scales of the order of 10^8 yr, which corresponds to the radio activity lifetime; the strong dependence of the local birthrate on the colors of the host galaxies is related to the time-scales of the order of the galaxy color evolution (i.e., $0.5 - 1$ Gyr); the evolution of the SN Ia birthrate with redshift is sensitive to the long time-scales (a few Gyr) (for details see Mannucci et al. 2006). According to the present observational results, Mannucci et al. (2006) found that they can be best matched by a bimodal delay time distribution, in which about half of the SNe Ia explode soon after starburst, with a delay time less than $\sim 10^8$ yr, while those remaining have a much wider distribution, which can be well described by an exponential function with a decay time of about 3 Gyr (see also Mannucci 2008). Note that Scannapieco & Bildsten (2005) explored the two components of SN Ia birthrates and found that a young SN Ia population may be helpful to explain the Fe content of the intracluster medium in galaxy clusters. Moreover, by investigating the star formation history of 257 SN Ia host galaxies, Aubourg et al. (2008) recently found evidence of a short-lived population of SN Ia progenitors with lifetimes of less than 180 Myr.

Over the last decades, two competing progenitor models of SNe Ia were discussed frequently, i.e., the single-degenerate (SD) and double-degenerate (DD) models. Of these two progenitor models, the SD model (Whelan & Iben 1973; Nomoto et al. 1984; Fedorova et al. 2004; Han 2008; Meng et al. 2009) is widely accepted at present. It is suggested that the DD model, which involves the merger of two CO WDs (Iben & Tutukov 1984; Webbink 1984; Han 1998), likely leads to an accretion-induced collapse rather than a SN Ia (Nomoto & Iben 1985; Saio & Nomoto 1985; Timmes et al. 1994). For the SD model, the companion is probably a MS star or a slightly evolved subgiant star (WD + MS channel), or a red-giant star (WD + RG channel). However, these two SD channels did not predict such young SN Ia populations (Hachisu et al. 1996, 1999a, 1999b; Li & van den Heuvel 1997; Langer 2000; Han & Podsiadlowski 2004, 2006).[4]

Wang et al. (2009) recently studied a WD + He star channel for the SD model to produce SNe Ia. In the study they carried out detailed binary evolution calculations of this channel for about 2600 close WD binaries with metallicity $Z = 0.02$, in which a CO WD accretes material from a He MS star or a He subgiant to increase its mass to the Chandrasekhar-mass limit. The study

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[4] Note that Hachisu et al. (2008) investigated new evolutionary models for SN Ia progenitors, introducing the mass-stripping effect on a MS or slightly evolved companion star by winds from a mass-accreting WD. The model can explain the presence of very young ($\lesssim 10^8$ yr) populations of SN Ia progenitors, but the model depends on the efficiency of the mass-stripping effect.

showed the SN Ia production regions in the $(\log P^{\rm i}, M_2^{\rm i})$ plane (see Fig. 8 of Wang et al. 2009), where $P^{\rm i}$ and $M_2^{\rm i}$ are the orbital period and the mass of the He companion star at the onset of the Roche lobe overflow (RLOF), respectively, and indicated that this channel is noteworthy for producing SNe Ia. Because the WD + He star systems are from intermediate mass binary systems, this channel is likely to explain SNe Ia with short delay times. However, SN Ia birthrates and delay times through this channel are not well known from a viewpoint of the binary population synthesis (BPS).

The purpose of this paper is to study SN Ia birthrates for the WD + He star channel and to explore possible SN Ia progenitor systems with short delay times from this channel. In Section 2, we describe the BPS approach for the WD + He star channel. The simulation results of the BPS approach is shown in Section 3. Finally, discussion and conclusion are given in Section 4.

2. BINARY POPULATION SYNTHESIS

In order to investigate SN Ia birthrates and delay times for the WD + He star channel, we have performed a series of Monte Carlo simulations in the BPS study. In each simulation, by using the Hurley's rapid binary evolution code (Hurley et al. 2000, 2002), we have followed the evolution of 4×10^7 sample binaries from the star formation to the formation of the WD + He star systems according to three evolutionary channels (Sect. 2.2). We assumed that, if the parameters of a CO WD + He star system at the onset of the RLOF are located in the SN Ia production regions in the $(\log P^{\rm i}, M_2^{\rm i})$ plane (Fig. 8 of Wang et al. 2009), a SN Ia is produced. Hereafter, we use the term *primordial* to represent the binaries before the formation of WD + He star systems.

2.1. *Common Envelope in Binary Evolution*

When the primordial primary (massive star) in a binary system fills its Roche lobe, the primordial mass ratio (primary to secondary) is crucial for the mass transfer. If it is larger than a critical mass ratio, $q_{\rm c}$, the mass transfer may be dynamically unstable and a common envelope (CE) forms (Paczyński 1976). The mass ratio $q_{\rm c}$ varies with the evolutionary state of the primordial primary at the onset of RLOF (Hjellming & Webbink 1987; Webbink 1988; Han et al. 2002; Podsiadlowski et al. 2002). In this study we adopt $q_{\rm c} = 4.0$ when the primary is in the MS stage or Hertzsprung gap. This value is supported by detailed binary evolution studies (Han et al. 2000; Chen & Han 2002, 2003). If the primordial primary is on the first giant branch (FGB) or asymptotic giant branch (AGB) stage, we use

$$q_{\rm c} = [1.67 - x + 2(\frac{M_{\rm c1}^{\rm P}}{M_1^{\rm P}})^5]/2.13, \quad (1)$$

where $M_1^{\rm P}$ is the mass of the primordial primary, $M_{\rm c1}^{\rm P}$ is the core mass of the primordial primary, and $x = {\rm d}\ln R_1^{\rm P}/{\rm d}\ln M_1^{\rm P}$ is the mass-radius exponent of the primordial primary and varies with composition. If the mass donor stars (primaries) are naked He giants, $q_{\rm c} = 0.748$ based on equation (1) (see Hurley et al. 2002 for details).

When a CE forms, the embedded in the CE is a 'new' binary consisting of the dense core of the primordial primary and the primordial secondary. Owing to frictional drag within the envelope, the orbit of the 'new' binary decays and a large part of the orbital energy released in the spiral-in process is injected into the envelope (Livio & Soker 1988). The CE ejection is still an open problem. Here, we use the standard energy equations (Webbink 1984) to calculate the output of the CE phase. The CE is ejected if

$$\alpha_{\rm ce}\left(\frac{GM_{\rm don}^{\rm f}M_{\rm acc}}{2a_{\rm f}} - \frac{GM_{\rm don}^{\rm i}M_{\rm acc}}{2a_{\rm i}}\right) = \frac{GM_{\rm don}^{\rm i}M_{\rm env}}{\lambda R_{\rm don}}, \quad (2)$$

where λ is a structure parameter that depends on the evolutionary stage of the donor, $M_{\rm don}$ is the mass of the donor, $M_{\rm acc}$ is the mass of the accretor, a is the orbital separation, $M_{\rm env}$ is the mass of the donor's envelope, $R_{\rm don}$ is the radius of the donor, and the indices i and f denote the initial and final values, respectively. The right side of the equation represents the binding energy of the CE, the left side shows the difference between the final and initial orbital energy, and $\alpha_{\rm ce}$ is the CE ejection efficiency, i.e., the fraction of the released orbital energy used to eject the CE. For this prescription of the CE ejection, there are two highly uncertain parameters (i.e., λ and $\alpha_{\rm ce}$). We usually set λ to be 0.5 to constrain $\alpha_{\rm ce}$ (de Kool 1990), although an exact calculation should take into account the issue that λ depends on the stellar structure. In principle, we expect $0 < \alpha_{\rm ce} \leq 1$, but we often find that $\alpha_{\rm ce}$ exceeds 1 for the purpose of explaining observed binaries. This may indicate that other energy sources may also contribute to the ejection of the envelope, e.g., the internal energy of the envelope (Han et al. 1994, 1995; Podsiadlowski et al. 2003; Webbink 2008). As in previous studies, we combine $\alpha_{\rm ce}$ and λ into one free parameter $\alpha_{\rm ce}\lambda$, and set it to be 0.5 and 1.5 (e.g., Lü et al. 2006).

2.2. *Evolutionary Channels to WD + He Star Systems*

According to the evolutionary phase of the primordial primary at the beginning of the first RLOF, there are three channels which can produce CO WD + He star systems and then produce SNe Ia.

(1) *He star channel.* The primordial primary first fills its Roche lobe when it is in the subgiant or RG stage (Case B mass transfer defined by Kippenhahn & Weigert 1967). At the end of the RLOF, the primary becomes a He star and continues to evolve. After the exhaustion of central He, the He star which now contains a CO core may fill its Roche lobe again due to expansion of the He star itself, and transfer its remaining He-rich envelope to the MS companion star, eventually leading to the formation of a CO WD + MS system. After that, the MS companion star continues to evolve and fills its Roche lobe in the subgiant or RG stage. A CE is possibly formed quickly because of dynamically unstable mass transfer. If the CE can be ejected, a close CO WD + He star system is then produced. The CO WD + He star system continues to evolve, and the He star may fill its Roche lobe again (due to orbit decay induced by the gravitational wave radiation or the expansion of the He star itself), and transfer some material onto the surface of the CO WD. The accreted He may be converted into C and O via He-shell burning, and the CO WD increases in mass and explodes as a SN Ia when its mass reaches the Chandrasekhar mass limit. For this channel,

SN Ia explosions occur for the ranges $M_{1,\rm i} \sim 5.0$–$8.0\,M_\odot$, $M_{2,\rm i} \sim 2.0 - 6.5\,M_\odot$ and $P^{\rm i} \sim 10 - 40$ days, where $M_{1,\rm i}$, $M_{2,\rm i}$ and $P^{\rm i}$ are the initial mass of the primary and the secondary at ZAMS, and the initial orbital period of a binary system.

(2) *EAGB channel.* If the primordial primary is on the early AGB (EAGB, i.e., He is exhausted in the center of the star while thermal pulses have not yet started), a CE will be formed because of dynamically unstable mass transfer. After the CE is ejected, the orbit decays and the primordial primary becomes a He RG. The He RG may fill its Roche lobe and start mass transfer, which is likely stable and leaves a CO WD + MS system. The following evolution of the CO WD + MS system is similar to that in the *He star channel* above, and may form a CO WD + He star system and finally produce a SN Ia. For this channel, SN Ia explosions occur for the ranges $M_{1,\rm i} \sim 6.0 - 6.5\,M_\odot$, $M_{2,\rm i} \sim 5.5 - 6.0\,M_\odot$ and $P^{\rm i} \sim 300 - 1000$ days.

(3) *TPAGB channel.* The primordial primary fills its Roche lobe at the thermal pulsing AGB (TPAGB) stage, and the companion star evolves to a He-core burning stage. A CE is easily formed owing to dynamically unstable mass transfer during the RLOF. After the CE ejection, the primordial primary becomes a CO WD, then a CO WD + He star system is produced. The following evolution of the CO WD + He star system is similar to that in two channels above, i.e., a SN Ia may be produced finally. For this channel, SN Ia explosions occur for the ranges $M_{1,\rm i} \sim 5.5 - 6.5\,M_\odot$, $M_{2,\rm i} \sim 5.0 - 6.0\,M_\odot$ and $P^{\rm i} \gtrsim 1000$ days.

2.3. *Basic Parameters for Monte Carlo Simulations*

In the BPS study, the Monte Carlo simulation requires as input the initial mass function (IMF) of the primary, the mass-ratio distribution, the distribution of initial orbital separations, the eccentricity distribution of binary orbit and the star formation rate (SFR).

(1) The IMF of Miller & Scalo (1979, MS79) is adopted. The primordial primary is generated according to the formula of Eggleton et al. (1989)

$$M_1^{\rm p} = \frac{0.19X}{(1-X)^{0.75} + 0.032(1-X)^{0.25}}, \qquad (3)$$

where X is a random number uniformly distributed in the range [0, 1] and $M_1^{\rm p}$ is the mass of the primordial primary, which ranges from $0.1\,M_\odot$ to $100\,M_\odot$. The studies of the IMF by Kroupa et al. (1993) and Zoccali et al. (2000) support this IMF. As an alternative IMF we also consider the IMF of Scalo (1986, S86)

$$M_1^{\rm p} = 0.3\left(\frac{X}{1-X}\right)^{0.55}, \qquad (4)$$

where the meanings of X and $M_1^{\rm p}$ are similar to that of equation (3).

(2) The initial mass-ratio distribution of the binaries, q', is quite uncertain for binary evolution. For simplicity, we take a constant mass-ratio distribution (Mazeh et al. 1992; Goldberg & Mazeh 1994):

$$n(q') = 1, \qquad 0 < q' \leq 1, \qquad (5)$$

where $q' = M_2^{\rm p}/M_1^{\rm p}$. This constant mass-ratio distribution is supported by the study of Shatsky & Tokovinin (2002). As alternatives we also consider a rising mass ratio distribution

$$n(q') = 2q', \qquad 0 \leq q' \leq 1, \qquad (6)$$

and the case where both binary components are chosen randomly and independently from the same IMF (uncorrelated).

(3) We assume that all stars are members of binary systems and that the distribution of separations is constant in $\log a$ for wide binaries, where a is separation and falls off smoothly at small separation:

$$a \cdot n(a) = \begin{cases} \alpha_{\rm sep}(a/a_0)^{\rm m}, & a \leq a_0, \\ \alpha_{\rm sep}, & a_0 < a < a_1, \end{cases} \qquad (7)$$

where $\alpha_{\rm sep} \approx 0.07$, $a_0 = 10\,R_\odot$, $a_1 = 5.75 \times 10^6\,R_\odot = 0.13$ pc and $m \approx 1.2$. This distribution implies that the numbers of wide binary systems per logarithmic interval are equal, and that about 50 percent of stellar systems have orbital periods less than 100 yr (Han et al. 1995).

(4) A circular orbit is assumed for all binaries. The orbits of semidetached binaries are generally circularized by the tidal force on a timescale which is much smaller than the nuclear timescale. Moreover, a binary is expected to become circularized during the RLOF. As an alternative, we also consider a uniform eccentricity distribution in the range [0, 1].

(5) We simply assume a constant SFR over the last 15 Gyr or, alternatively, as a delta function, i.e., a single starburst. In the case of a constant SFR, we assume that a binary calibrated with its primary more massive than $0.8\,M_\odot$ is formed annually (see Iben & Tutukov 1984; Han et al. 1995; Hurley et al. 2002). From this calibration, we can get SFR $= 5\,M_\odot{\rm yr}^{-1}$ (see also Willems & Kolb 2004). For the case of a single starburst, we assume a burst producing $10^{11}\,M_\odot$ in stars. In fact, the SFR in a galaxy is neither a constant nor a delta function over the last 15 Gyr. A galaxy may have a complicated star formation history. We only choose these two extremes for a simplicity. A constant SFR is similar to the situation of our Galaxy (Yungelson & Livio 1998; Han & Podsiadlowski 2004), while a delta function to the situation of elliptical galaxies or globular clusters. Under the assumption of the SFR as a delta function, one can obtain the delay time of SNe Ia from a progenitor channel, and then to compare with that of observations (e.g., Han & Podsiadlowski 2004).

3. THE RESULTS OF BINARY POPULATION SYNTHESIS

3.1. *Birthrates of SNe Ia*

We performed six sets of simulations (see Table 1) with metallicity $Z = 0.02$ to systematically investigate Galactic birthrates of SNe Ia for the WD + He star channel, where set 1 is our standard model with the best choice of model parameters (e.g., Han et al. 2002, 2003, 2007). We vary the model parameters in the other sets to examine their influences on the final results.

In Figure 1, we show Galactic birthrates of SNe Ia for the WD + He star channel by adopting $Z = 0.02$ and SFR $= 5\,M_\odot{\rm yr}^{-1}$. The simulation for our standard model (set 1) gives Galactic SN Ia birthrate of $\sim 0.3 \times 10^{-3}$ yr^{-1}, which is lower than that inferred observationally (i.e., $3 - 4 \times 10^{-3}$ yr^{-1}; van den Bergh & Tammann 1991; Cappellaro & Turatto 1997). This

TABLE 1
GALACTIC BIRTHRATES OF SNE IA FOR DIFFERENT SIMULATION SETS, WHERE SET 1 IS OUR STANDARD MODEL. $\alpha_{\rm ce}\lambda$ = CE EJECTION PARAMETER; $n(q')$ = INITIAL MASS RATIO DISTRIBUTION; IMF = INITIAL MASS FUNCTION; ecc = ECCENTRICITY DISTRIBUTION OF BINARY ORBIT; ν = GALACTIC BIRTHRATES OF SNE IA.

Set	$\alpha_{\rm ce}\lambda$	$n(q')$	IMF	ecc	ν ($10^{-3}\,{\rm yr}^{-1}$)
1	0.5	Constant	MS79	Circular	0.295
2	1.5	Constant	MS79	Circular	0.302
3	1.5	Constant	MS79	Uniform	0.284
4	1.5	Constant	S86	Circular	0.168
5	1.5	Rising	MS79	Circular	0.232
6	1.5	Uncorrelated	MS79	Circular	0.040

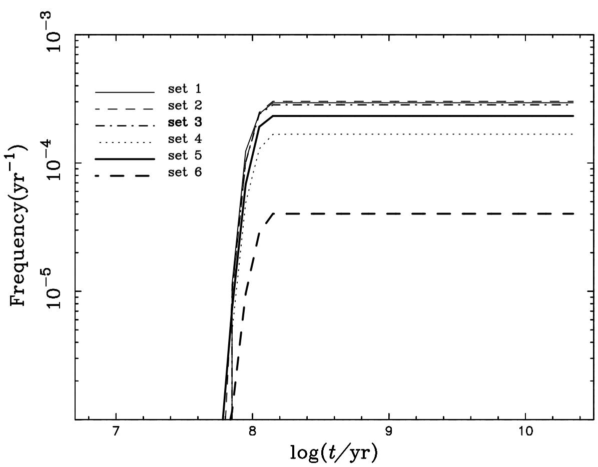

FIG. 1.— The evolution of Galactic birthrates of SNe Ia for a constant star formation rate ($Z = 0.02$, SFR $= 5\,M_{\odot}{\rm yr}^{-1}$). The key to the line-styles representing different sets is given in the upper left corner. The results of sets 2 and 3 almost coincide with that of set 1.

implies that the WD + He star channel is only a subclass of SN Ia production, and there may be some other channels or mechanisms also contributing to SNe Ia, e.g., WD + MS channel, WD + RG channel or double-degenerate channel (see Meng et al. 2009 for details). Especially, as mentioned by Han & Podsiadlowski (2004), the WD + MS channel can give a Galactic birthrate of $\sim 0.6-0.8\times10^{-3}$ yr^{-1}, and is considered to be an important channel to produce SNe Ia.

According to the results of the six sets of Monte Carlo simulations, we find that the BPS is sensitive to uncertainties in some input parameters, in particular the mass-ratio distribution. If we adopt a mass-ratio distribution for un-correlated component masses (set 6), the birthrate will decrease to be $\sim 4\times10^{-5}\,{\rm yr}^{-1}$, as most of the donors in the WD + He star channel are not very massive which has the consequence that WDs cannot accrete enough mass to reach the Chandrasekhar-mass limit.

The SN Ia birthrate in galaxies is the convolution of the distribution of the delay times (DDT) with the star formation history (SFH) (e.g., Greggio et al. 2008):

$$\nu(t) = \int_0^t SFR(t-t')DDT(t')dt', \qquad (8)$$

where the SFR is the star formation rate, and t' is the delay times of SNe Ia. Due to a constant SFR adopted in this paper, the SN Ia birthrate $\nu(t)$ is only related to

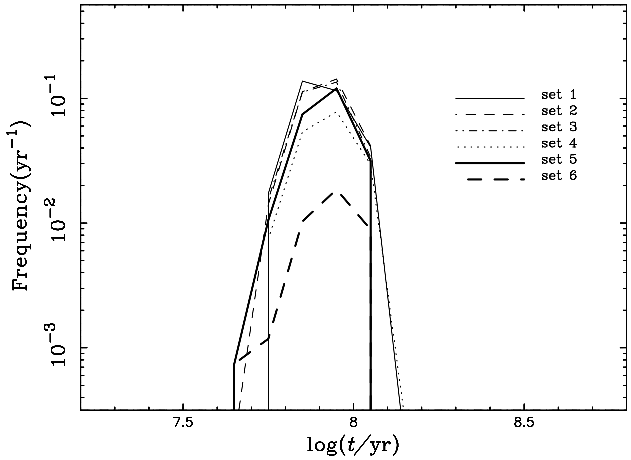

FIG. 2.— Similar to Fig. 1, but for a single starburst with a total mass of $10^{11}\,M_{\odot}$. The result of set 3 almost coincides with that of set 2.

the DDT, which can be expressed by

$$DDT(t) = \begin{cases} 0, & t < {\rm t}_1, \\ DDT'(t), & {\rm t}_1 \le t \le {\rm t}_2, \\ 0, & t > {\rm t}_2, \end{cases} \qquad (9)$$

where $\rm t_1$ and $\rm t_2$ are the minimum and maximum delay times of SNe Ia, respectively, and the DDT' is the distribution of the delay times between $\rm t_1$ and $\rm t_2$. When t is larger than the $\rm t_2$, the equation (8) can be written as

$$\nu(t) = {\rm SFR}\int_{\rm t_1}^{\rm t_2} DDT'(t')dt' = {\rm constant}. \qquad (10)$$

Therefore, the SN Ia birthrates shown in figure 1 seems to be so completely flat after the first rise.

Figure 2 displays the evolution of SN Ia birthrates for a single starburst with a total mass of $10^{11}\,M_{\odot}$. In the figure we see that SN Ia explosions occur between $\sim 4.5\times10^7$ yr and $\sim 1.4\times10^8$ yr after the starburst, which can explain SNe Ia with short delay times (Scannapieco & Bildsten 2005; Mannucci et al. 2006; Aubourg et al. 2008). The minimum delay time in the figure is mainly decided by the MS lifetime of a $8\,M_{\odot}$ star (it is also the maximum mass for the progenitors of CO WDs). Moreover, after the primordial binary system evolves to a WD + He star system, the MS lifetime of the He companion star also contributes to the minimum time, but the time is short, e.g., the MS lifetime of a $1\,M_{\odot}$ He star is only about 15 Myr (Eggleton 2006).

3.2. *Distribution of Initial Parameters of WD + He Star Systems for SNe Ia*

Observationally, some WD + He star systems are possible SN Ia progenitors (Wang et al. 2009). Further investigations are necessary for final confirmation of this (from both observations and theories). In this section, we will present some properties of initial WD + He star systems for SNe Ia according to our BPS approach, which may help to search for potential SN Ia progenitors.

Figure 3 shows the distribution of the initial orbital periods of the WD + He star systems that ultimately produce SNe Ia with different $\alpha_{\rm ce}\lambda$. The simulation uses a metallicity $Z = 0.02$ and a constant initial mass-ratio distribution. The figure displays a result of the current epoch for a constant SFR. In the figure we can see that

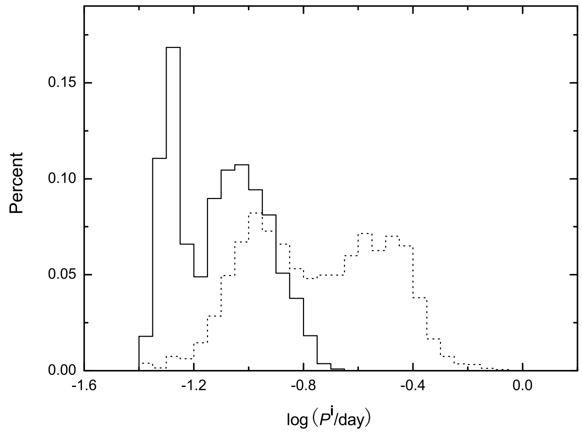

FIG. 3.— The distribution of the initial orbital periods of the WD + He star systems which can ultimately produce SNe Ia for different $\alpha_{ce}\lambda$. The simulation uses a metallicity $Z = 0.02$ and a constant initial mass-ratio distribution. The solid and the dotted histograms represent the cases with $\alpha_{ce}\lambda = 0.5$ (set 1) and $\alpha_{ce}\lambda = 1.5$ (set 2), respectively. The number in every case is normalized to 1.

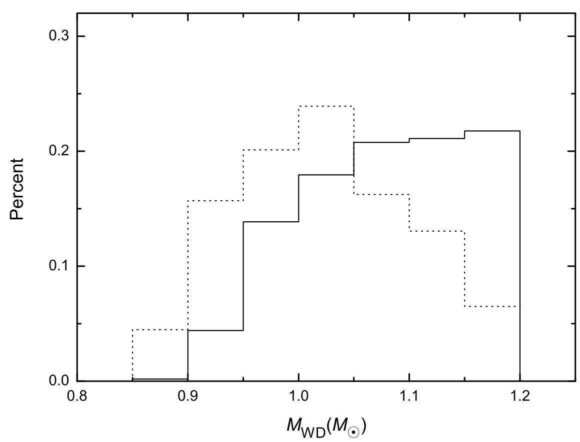

FIG. 4.— Similar to Fig. 3, but for the distribution of the initial masses of the CO WDs.

there are obviously two peaks for each case. The left peak in these two cases results from the *He star channel*. Many of the SNe Ia in the right peak are also from the *He star channel*, while others from the *EAGB channel* and the *TPAGB channel* (see Sect. 2.2). The *He star channel* has an important contribution to the formation of SNe Ia. This figure also shows that a high value of $\alpha_{ce}\lambda$ leads to wider WD binaries, since a high value of $\alpha_{ce}\lambda$ is easier to eject the CE in the binary evolution.

Figure 4 represents the distribution of the initial masses of the CO WDs. In the figure, a low value of $\alpha_{ce}\lambda$ tends to have larger WD masses on average. The *He star channel* in Sect. 2.2, which allows stable RLOF to produce massive WDs (rather lead to dynamical mass transfer and a CE phase), is useful to understand this trend. According to our BPS simulations, we find that a

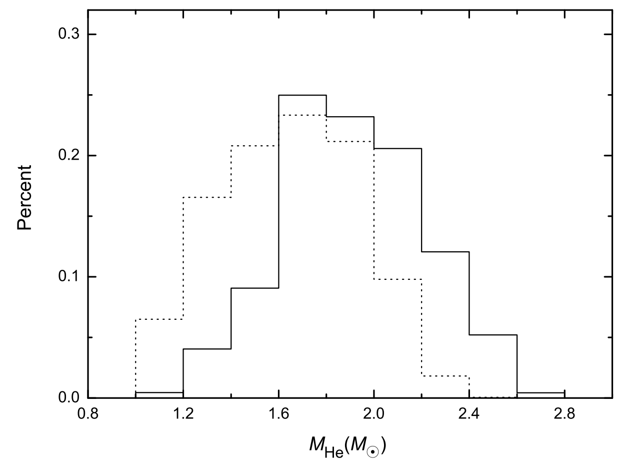

FIG. 5.— Similar to Fig. 3, but for the distribution of the initial masses of the He donor stars.

low value of $\alpha_{ce}\lambda$ will produce more SNe Ia through the *He star channel* than other two channels, and then produce more massive WDs on average. Figure 5 displays the distribution of the initial masses of the He donor stars. A low value of $\alpha_{ce}\lambda$ in the figure tends to have larger He star masses on average. This is also related to the stable RLOF, which leads to more massive companion star resulting in the final larger He-core mass (He star mass). Moreover, a massive He donor star in the WD + He star channel will evolve more quickly and hence produce a SN at an earlier time.

When the WDs in Figure 4 increase their masses to the Chandrasekhar-mass limit, they will explode as SNe Ia. Meanwhile, the He donor stars in Figure 5, which afford material to the WDs though the RLOF, will loss a significant amount of masses. We find that the He stars have masses $\sim 0.6 - 1.7\,M_{\odot}$ at the moment of SN explosions. Marietta et al. (2000) presented several high-resolution two-dimensional numerical simulations of the impacts of SN Ia explosions with companions. The impact makes the companion in the WD + MS channel lose a mass of $0.15 - 0.17\,M_{\odot}$, but the impact in the WD + He star channel is still unknown. The companion in the WD + He star channel may lose more masses than that of the WD + MS channel. This is because the orbit separation at the moment of SN explosion from this channel is significantly less than that of the WD + MS channel, which may result in a much stronger impact to the companion. The surviving companion star from the WD + He star channel could be verified by future observations.

4. DISCUSSION AND CONCLUSION

Wang et al. (2009), based on equation (1) of Iben & Tutukov (1984), estimated the potential SN Ia birthrate through the WD + He star channel to be $\sim 1.2 \times 10^{-3}\,\mathrm{yr}^{-1}$ in the Galaxy. The birthrate from Wang et al. (2009) is higher than that in this paper, this is due to the fact that the long orbit period (i.e., $\gtrsim 1$ day in Fig. 8 of Wang et al. 2009) systems, which are considered to produce SNe Ia in equation (1) of Iben & Tutukov (1984), do not contribute to SNe Ia in the simulation results of this paper. In addition, Umeda et al. (1999a)

concluded that the upper limit mass of CO cores born in binaries is about 1.07 $M_{\odot}$. If this value is adopted as the upper limit of the CO WD, the birthrate of SNe Ia from this channel will decrease to be $\sim 0.2 \times 10^{-3}\,\mathrm{yr}^{-1}$ in the Galaxy according to our standard model.

In this paper we assume that all stars are in binaries and about 50 percent of stellar systems have orbital periods less than 100 yr. In fact, it is known not to be the case, and the binary fractions may depend on metallicity, environment, spectral type, etc. If we adopt 40 percent of stellar systems have orbital periods below 100 yr by adjusting the parameters in equation (7), we estimate that the birthrate of SNe Ia from this channel will decrease to be $\sim 0.24 \times 10^{-3}\,\mathrm{yr}^{-1}$ for our standard model.

SNe Ia from the WD + He star channel usually have massive CO WDs as their progenitors. Some previous studies showed that a massive CO WD leads to a lower C/O ratio in the Chandrasekhar-mass WD, and thus a lower amount of ^{56}Ni synthesized in the thermonuclear explosion, which results in a lower luminosity of SNe Ia (Umeda et al. 1999b; Nomoto et al. 1999, 2003). However, brighter SNe Ia more frequently occur in active star formation galaxies (Hamuy et al. 1995, 1996), in which the young stellar population implies that these SNe Ia have short delay times (see also Aubourg et al. 2008), i.e., the CO WD + He star channel might produce brighter SNe Ia. Therefore, it is difficult to explain SN Ia diversity by using the C/O ratio. Note that 3D simulations about SN Ia explosions by Röpke & Hillebrandt (2004) also indicated that different C/O ratios have a negligible effect on the amount of ^{56}Ni produced. To understand the diversity of SN Ia explosions, the formation of brighter SNe Ia should be explored in future investigations.

It is suggested that the WD + He star systems may appear as supersoft X-ray sources (SSSs) prior to SN Ia explosions (Iben & Tutukov 1994; Yoon & Langer 2003; Wang et al. 2009). Recently, Di Stefano & Kong (2003) used a set of conservative criteria, applicable to *Chandra* data, to identify luminous SSSs in four external galaxies (an elliptical galaxy, NGC 4967; two face-on spiral galaxies, M101 and M83; and an interacting galaxy, M51). They found that in every galaxy there are at least several hundred luminous SSSs with a luminosity of $10^{37}\,\mathrm{erg\,s^{-1}}$, and that in spiral galaxies M101, M83 and M51, the SSSs appear to be associated with spiral arms. This may indicate that some SSSs are young systems, possibly younger than 10^8 yr. Note that a WD + He star system has X-ray luminosity around $10^{37} - 10^{38}\,\mathrm{erg\,s^{-1}}$ when He burning is stable on the surface of the WD (Wang et al. 2009). Meanwhile, the distribution of SNe Ia with short delay times associated with galactic spiral arms (Bartunov et al. 1994; Della Valle & Livio 1994). Therefore, we emphasize that these WD + He star systems may be related to the young SSSs prior to SN Ia explosions.

The most important conclusion of this study is that the WD + He star channel can explain SNe Ia with short delay times ($\sim 4.5 \times 10^7 - 1.4 \times 10^8$ yr), which is consistent with recent observational implications of young populations of some SN Ia progenitors (Scannapieco & Bildsten 2005; Mannucci et al. 2006; Aubourg et al. 2008). The young population of SNe Ia may have an effect on models of galactic chemical evolution, since they would return large amounts of iron to the interstellar medium much earlier than previously thought. It may also have an impact on cosmology, as they are used as cosmological distance indicators.

We thank an anonymous referee for his/her valuable comments that helped to improve the paper. BW thanks Dr. Richard Pokorny for improving the English language of the original manuscript. This work is supported by the National Natural Science Foundation of China (Grant Nos. 10521001, 2007CB815406 and 10603013), the Foundation of the Chinese Academy of Sciences (Grant No. 06YQ011001) and the Yunnan Natural Science Foundation (Grant No. 08YJ041001).

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